

Impact of load distribution on energy generation in a piezoelectric floor prototype

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ABSTRACT

The increasing global energy demand necessitates the development of sustainable and environmentally friendly alternative energy sources. This study presents the design and evaluation of a piezoelectric floor prototype comprising 128 parallel-arranged PZT units, supported by spring pillars as a medium for force transmission. The novelty of this research lies in analysing the effects of loading patterns (walking and jumping) and user mass variations (69 kg and 98 kg) on electrical output performance. Experimental results indicate that jumping patterns generate higher voltage and current compared to walking, while increased mass significantly enhances energy output. The highest performance was observed under the jumping condition with a 98 kg load, yielding an average voltage of 8.9 V and a current of 11.7 mA. These findings confirm that variations in loading pattern and mass directly affect system performance and highlight the practical potential of piezoelectric flooring for low-power applications, such as IoT devices. Further research is recommended to improve signal stability and integrate energy storage systems to support field-scale implementation.

Keywords: energy harvesting, piezoelectric, prototype, PZT, renewable energy, smart floor

INTRODUCTION

The growing global population dynamics pose fundamental challenges to meeting energy demands. As the availability of non-renewable fossil fuels continues to diminish, complex consequences inevitably emerge, including environmental degradation and the intensification of global climate change (Divine Kobbi et al., 2024). This situation underscores the urgency of developing renewable energy sources that are more

environmentally friendly and sustainability-oriented (Dwisari et al., 2023).

Within the framework of exploring environmentally friendly alternative energy sources, the utilisation of mechanical energy generated from human activities has emerged as a promising approach. (Stiawan and Taufiq, 2020). The implementation of piezoelectric technology enables the conversion of mechanical energy from human footsteps into electrical energy, thereby offering an innovative

solution to the challenges of energy sustainability (Putra et al., 2018). Several previous studies have highlighted the importance of optimising piezoelectric system designs to enhance the efficiency of energy harvesting (He et al., 2019). Developed a piezoelectric floor design based on a double-layer structure combined with a spring mechanism, which induced bending deformation in the piezoelectric material. The results demonstrated a significant improvement in electrical output, increasing from 18.8 V to 51.4 V.

In addition, research conducted by (Susanti and Bistama, 2020) Their findings revealed that a series configuration was capable of producing higher voltage compared to a parallel configuration, while the parallel configuration demonstrated superior performance in generating current. These results suggest that the selection of circuit configuration should be aligned with the specific requirements of the intended load application.

Additionally, another critical factor is the number of piezoelectric elements used. For instance, a study conducted by (Hasan et al., 2021) Investigated variations in the number of piezoelectric elements 28, 56, 70, 84, and 98 units. A corresponding increase in harvested energy output was observed, ranging from approximately 0.05 joules to 1.9 joules, as the number of elements increased. These findings confirm that increasing the number of piezoelectric elements directly contributes to enhancing the harvestable energy output.

Nevertheless, these three studies have primarily focused on mechanical design aspects, circuit configurations, and the number of piezoelectric elements, without addressing variations in loading patterns arising from human activities. In reality, activity patterns such as walking and jumping are likely to impose different loading characteristics on piezoelectric systems. Therefore, the present study aims to fill this gap by analysing the effect of loading pattern variations on the performance of a piezoelectric floor prototype. Furthermore, the findings are expected to provide deeper insights into the interaction between dynamic human loads and the response of piezoelectric floor systems, while offering a scientific contribution in the form of an experimental investigation that may serve as a foundation for developing more efficient piezoelectric floor systems in the future.

MATERIAL AND METHOD

Material

Commercially available piezoelectric materials are generally classified into two main categories: ceramic-based, such as Lead Zirconate Titanate (PZT), and polymer-based, such as Polyvinylidene Fluoride (PVDF) (Nivedhitha and Jeyanthi, 2023). PVDF is known for its flexibility, lightweight nature, and relative ease of application, whereas PZT exhibits more rigid mechanical properties but offers superior piezoelectric performance (Aydin and Çelebi, 2023).

Comparative studies have reported that PZT possesses the highest piezoelectric coefficient

among commonly available commercial materials. The piezoelectric constant (d) of PZT can reach up to 289 pC/N, which is substantially higher than PVDF, measured at approximately -33 pC/N (Aydin & Çelebi, 2023). This high coefficient is significant, as it directly influences the material's ability to generate electrical voltage when subjected to mechanical force.

Theoretically, the output voltage of a piezoelectric element under open-circuit conditions can be expressed as:

$$V = \frac{d \times F}{C} \quad (1)$$

where:

V = Output voltage (V)

d = Piezoelectric constant (pC/N)

F = Applied mechanical force (N)

C = Capacitance of the piezoelectric element (F).

Based on this equation, the greater the value of the piezoelectric constant (d), the higher the voltage generated for a given mechanical force. However, although the theoretically predicted voltage can reach relatively high values, the output current of piezoelectric elements remains comparatively low, typically in the microampere range. Several studies have reported that the output current of a single piezoelectric element under standard mechanical loading conditions is approximately 5 μ A, thereby limiting its direct application in high-power systems. (Susanti and Bistama, 2020). The datasheet of the piezoelectric element is presented in Figure 1.

Specifications

Resonance Frequency	4.6kHz
Resonant Frequency Tolerance	± 0.5 kHz
Resonant Impedance (R1)	200 Ω
Capacitance	20nF
Capacitance Tolerance	$\pm 30\%$
Measurement Condition of Capacitance	[1kHz]
Operating Temperature Range	-20°C to 70°C
Storage Temperature Range	-30°C to 80°C
Shape	No lead wire
Plate Size	27mm
Element Size	19.7mm
Plate Material	Brass
Drive Type	External Drive
EIAJ Part Number	PD-SU2-C27-46
Mass	1968mg

Figure 1. Datasheet piezoelectric 27mm.

In this study, PZT-type piezoelectric elements with a capacitance of 20 nF and a diameter of 27 mm were employed, as specified in the component datasheet. The selection of PZT, with its high piezoelectric coefficient, was intended to achieve a more substantial voltage output compared to other materials such as PVDF, making it suitable for energy harvesting applications from human footfalls.

Method

This study employed a Research and Development (R&D) approach, which aimed not only to design and construct a piezoelectric floor prototype but also to experimentally evaluate its performance. The R&D method is commonly applied in engineering and product development research to generate artefacts (such as prototypes) that are subsequently tested, refined, and iteratively evaluated to achieve the desired functional and performance

objectives (Gustiani & Sriwijaya, 2023).

At the design stage, a total of 128 PZT piezoelectric discs were employed, each with a diameter of 27 mm and a capacitance of 20 nF. These piezoelectric elements were connected in a parallel configuration, as illustrated in Figure 2.

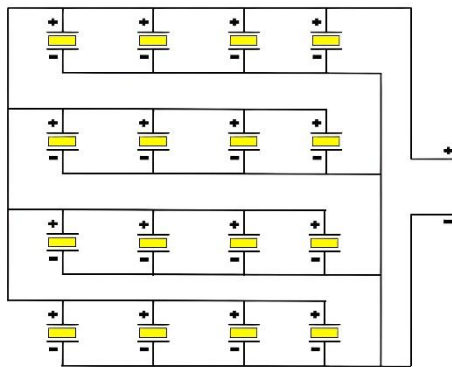


Figure 2. Parallel configuration of 27 mm PZT piezoelectric discs.

The parallel configuration was chosen with the expectation of producing a higher current output compared to a series configuration. This decision was based on the projected application of the piezoelectric floor system for battery charging, where current demand is more critical than voltage.

Nevertheless, in this study, the prototype was not directly tested with a battery charging circuit. Instead, a simple closed circuit with a 1 Ω resistive load was employed. This setup was intended to enable controlled measurements of voltage, current, and output energy, thereby facilitating more systematic analysis.

From the mechanical perspective, the prototype was designed without employing a double-layer structure as explored in previous studies. Instead, it utilised

the elastic effect of spring pillars placed beneath the prototype floor surface. These spring pillars served to enhance the deformation of the piezoelectric elements when subjected to forces generated by walking or jumping activities. With the inclusion of springs, the applied load was not only directly transferred to the piezoelectric elements. However, it was also amplified through elastic mechanisms, thereby increasing the amount of mechanical energy harvested. Additionally, the selection of wood-based tiles is informed by previous research considerations. Although ceramic tiles have been reported to provide higher energy output (Go et al., 2023). Wood was chosen in this study due to its superior mechanical durability. Recent studies indicate that wood exhibits excellent fatigue properties and can withstand up to millions of repeated loading cycles. (Schönbauer et al., 2022), making it more suitable for flooring applications subjected to repeated dynamic loads. The mechanical design of the prototype is illustrated in the following figure. The mechanical design of the prototype is illustrated in the following figure.

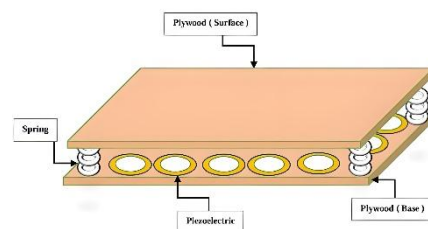


Figure 3. Mechanical Design of the Piezoelectric Floor Prototype.

By integrating both mechanical and electrical design aspects, this

study aims to provide a comprehensive overview of the potential of piezoelectric flooring as an energy-generating system, while also offering an empirical basis for further development in real-world applications, such as battery charging.

RESULT AND DISCUSSION

Following the design and experimental procedures described in the Methods section, electrical output data were obtained from the piezoelectric floor prototype under two loading patterns: walking and jumping. Each pattern was tested with two different user masses, 69 kg and 98 kg. For each combination of loading pattern and mass, ten repetitions were conducted to ensure more reliable results. The voltage data were recorded using a digital oscilloscope and subsequently presented in graphical form to facilitate the analysis of output patterns. Table 1 summarises the measurements obtained under the walking condition with a 69 kg mass, in accordance with the experimental conditions.

Table 1. Measurement results for the walking pattern on the prototype using a 69 kg mass.

Step	Volt (V)	Current (mA)
1	1,1	0,5
2	1,1	0,7
3	0,9	0,8
4	0,7	0,9
5	3,3	0,9
6	3,8	1,1
7	1,4	1,1
8	1,0	0,7
9	1,1	0,9
10	0,7	0,9
Average	1,51	0,85

The experimental results for a 69 kg mass indicated that the output voltage ranged from 0.7 V to 3.8 V, with an average value of 1.51 V. The generated current remained relatively stable, ranging from 0.5 mA to 1.1 mA, with an average of 0.85 mA. Voltage variations between steps reflect that the force applied by each footfall was not entirely constant, resulting in fluctuations in the electrical output. The highest voltage was recorded at the sixth step, reaching 3.8 V, indicating either a higher mechanical load or a more optimal force distribution at that point. Overall, these results suggest that, under a 69 kg load, the prototype is capable of generating a voltage level and a current in the milliamperage range. However, the average output remains relatively modest.

Subsequently, for comparative analysis, experiments were conducted with a different user mass, as summarised in Table 2.

Table 2. Measurement results for the walking pattern on the prototype using a 98 kg mass

Step	Volt (V)	Current (mA)
1	5,2	0,8
2	1,8	1,0
3	8,7	1,3
4	5,7	1,3
5	6,7	1,5
6	4,8	1,5
7	5,8	1,2
8	5,9	1,3
9	5,9	1,3
10	3,9	1,4
Average	5,44	1,26

For the 98 kg mass, the measurements exhibited higher voltage outputs, ranging from 1.8 V to 8.7 V, with an average of 5.44 V. The

generated current also increased, ranging from 0.8 mA to 1.5 mA, with an average of 1.26 mA. The highest voltage was recorded at the third step, reaching 8.7 V, indicating a direct relationship between increased mass and the magnitude of mechanical force transmitted to the piezoelectric elements. Compared to the 69 kg condition, the average voltage increased more than threefold, while the average current rose by approximately 48%.

These findings are consistent with the fundamental piezoelectric theory, which states that the output voltage is directly proportional to the applied mechanical force (Putra et al., 2023). An increased user mass results in higher compressive forces, leading to greater deformation of the piezoelectric elements. This suggests that the piezoelectric floor system may achieve more efficient energy harvesting when subjected to heavier loads or in environments with varying pedestrian traffic. Subsequently, the prototype was tested under a different loading pattern, namely jumping, using a 69 kg mass, with the results presented in Table 3.

Table 3. Measurement results for the jumping pattern on the prototype using a 69 kg mass

Step	Volt (V)	Current (mA)
1	7,0	4,0
2	7,1	4,3
3	6,2	4,3
4	8,2	4,5
5	8,3	4,1
6	6,7	2,4
7	9,5	4,5
8	4,4	4,4
9	4,9	2,5
10	4,5	2,5
Average	6,68	3,67

Testing under the jumping pattern with a 69 kg mass produced voltage outputs ranging from 4.4 V to 9.5 V, with an average of 6.68 V. The corresponding current values ranged from 2.4 mA to 4.5 mA, with an average of 3.67 mA. Compared to the walking pattern at the same mass (average voltage 1.51 V and current 0.85 mA), the average voltage increased more than fourfold, and the average current increased more than threefold. These results indicate that jumping exerts significantly higher dynamic forces than walking, resulting in greater deformation of the piezoelectric elements.

Nevertheless, measurements also revealed considerable variation in output between consecutive steps. For instance, at the seventh step, a maximum voltage of 9.5 V with a current of 4.5 mA was recorded. However, at the following step (eighth), the voltage dropped sharply to 4.4 V, although the current remained relatively high at 4.4 mA. This inconsistency is likely influenced by external factors such as jump intensity, landing precision, and load distribution across the prototype surface. Consequently, while jumping can generate higher energy output, its characteristics tend to be less stable compared to walking, which produces a more consistent signal.

Table 4. Measurement results for the jumping pattern on the prototype using a 98 kg mass

Step	Volt (V)	Current (mA)
1	9,1	7,5
2	8,5	7,0
3	10,6	11,8
4	7,2	16,1
5	10,8	14,9

6	9,6	10,3
7	7,2	13,4
8	10,4	12,3
9	9,5	11,5
10	6,1	11,9
Average	8,9	11,67

Under the jumping pattern with a 98 kg mass, the voltage output increased, ranging from 6.1 V to 10.8 V, with an average of 8.9 V. The generated current was considerably higher than under the 69 kg condition, ranging from 7.0 mA to 16.1 mA, with an average of 11.67 mA. The highest voltage peak was recorded at the fifth step, at 10.8 V, with a current of 14.9 mA. Meanwhile, the maximum current of 16.1 mA occurred at the fourth step.

Compared to the jumping condition with a 69 kg mass, increasing the mass from 69 kg to 98 kg resulted in an approximate 33% increase in average voltage, whereas the average current rose more than threefold. This indicates that the contribution of mass to mechanical force has a more pronounced effect on current output, while voltage increases moderately. Practically, this suggests that a piezoelectric system subjected to heavier loads is more suitable for applications requiring higher current supply, such as battery charging.

After processing the quantitative data, as presented in Tables 1 through 4, the analysis was further extended to monitor the output signals using an oscilloscope. The oscilloscope readings provided a qualitative overview of the voltage and current waveform shapes, complementing the numerical information presented in the tables. Thus, the integration of quantitative and qualitative results

enables a more comprehensive understanding of the prototype's performance under varying loading patterns and user masses. Figure 4 illustrates the oscilloscope signals obtained from the walking pattern test with a 69 kg mass.

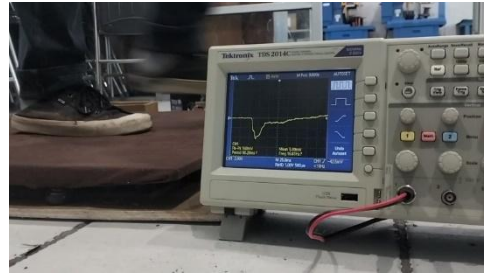


Figure 4. Oscilloscope signals obtained from the walking pattern test using a 69 kg mass.

Figure 4 presents the oscilloscope signals for the walking pattern with a 69 kg mass. The graph shows relatively low signal amplitudes with a consistent waveform, corresponding to the average outputs reported in Table 1 (1.51 V; 0.85 mA). These characteristics indicate that the walking pattern produces a more stable output, albeit with limited energy. Subsequently, the measurement results for the walking pattern with a 98 kg mass are presented in Figure 5.



Figure 5. Oscilloscope signals obtained from the walking pattern test using a 98 kg mass.

Figure 5, representing the walking pattern with a 98 kg mass, shows a notable increase in signal amplitude. The average outputs reported in Table 2 align with the graph, which exhibits higher voltage peaks. This indicates that user mass has a direct influence on the deformation of the piezoelectric elements. Following this test, an alternative loading pattern was applied, as illustrated in Figure 6.

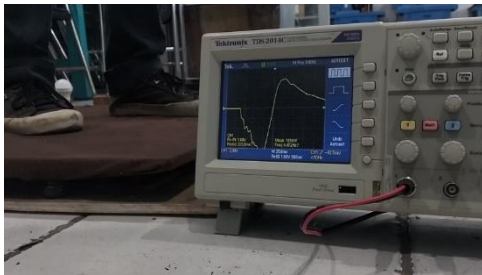


Figure 6. Oscilloscope signals obtained from the jumping pattern test using a 69 kg mass.

Figure 6 presents the oscilloscope signals for the jumping pattern with a 69 kg mass. Compared to the walking pattern, the waveform exhibits higher voltage peaks, consistent with the average outputs reported in Table 3. The observed waveforms are transient, characterised by rapid rises and gradual declines, reflecting the dynamic loading imposed by the jumping activity. However, the stability between consecutive steps is lower, likely influenced by variations in jump intensity and landing points. The subsequent measurements, conducted under the same loading pattern but with a different mass, are presented in Figure 7.

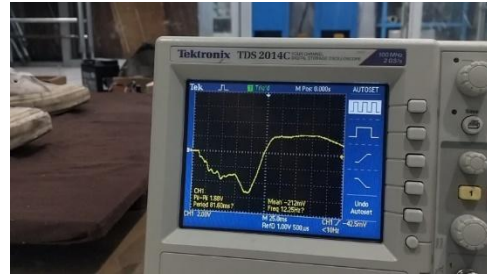


Figure 7. Oscilloscope signals obtained from the jumping pattern test using a 98 kg mass.

Figure 7 illustrates the jumping pattern with a 98 kg mass, which produced the highest signal amplitudes among all tests. The average outputs, reported in Table 4, were 8.9 V and 11.67 mA, indicating that a larger mass contributes significantly to the increase in current output. The waveform exhibits sharper and stronger peaks, confirming that the combination of a high mass and the jumping pattern provides the most favourable conditions for electricity generation.

Comparatively, it can be concluded that the walking pattern produces relatively stable outputs but with lower amplitudes, whereas the jumping pattern generates higher outputs but with less stability. Additionally, user mass was shown to have a significant effect on both voltage and, particularly, current outputs. Therefore, the piezoelectric floor demonstrates greater potential for optimal energy generation under heavy loads and dynamic activities. However, for practical applications such as battery charging, an appropriate energy management and storage system is still required to handle signal fluctuations.

Overall, these results indicate that variations in loading patterns and user mass have a substantial impact

on the output performance of the piezoelectric floor prototype. Increasing the user mass tends to enhance both voltage and current amplitudes, while the jumping pattern produces higher energy outputs compared to walking. Nevertheless, the walking pattern remains important, as it more accurately represents everyday activities in public spaces. This finding is consistent with the review by Sharma et al. (2022), which emphasised that the mechanical design and loading conditions strongly determine the energy output of piezoelectric floors. Consequently, structural optimisation strategies and the integration of power management systems are considered critical factors (Sharma et al., 2022).

Beyond the descriptive analysis of mean values, ranges, and oscilloscope output signals, a Two-Way Analysis of Variance (ANOVA) was performed to evaluate the influence of loading patterns (walking and jumping) and user mass (69 kg and 98 kg) on the prototype's output performance. Separate tests were conducted for voltage and current as dependent variables to determine the statistical significance of the observed differences. This inferential approach not only complements the descriptive findings but also provides more robust evidence, thereby enhancing the reliability of the conclusions. The ANOVA results for voltage obtained using Minitab are presented in Figure 8.

Analysis of Variance					
Source	DF	Adj SS	Adj MS	F-Value	P-Value
PATTERNS	1	186,192	186,192	74,67	0,000
MASS	1	94,556	94,556	37,92	0,000
PATTERNS*MASS	1	7,310	7,310	2,93	0,095
Error	36	89,769	2,494		
Total	39	377,828			

Figure 8. Two-Way ANOVA results for voltage obtained using Minitab.

The results of the two-way ANOVA indicate that both the loading pattern and the user's mass exert a significant influence on the output voltage of the piezoelectric floor prototype. The loading pattern factor yielded an F-value of 74.67 with $p = 0.000$, while the mass factor produced an F-value of 37.92 with $p = 0.000$. Since both p-values are far below the significance threshold of $\alpha = 0.05$ (95% confidence level), it can be concluded that statistically significant differences exist between walking and jumping conditions, as well as between body masses of 69 kg and 98 kg.

Conversely, the interaction between loading pattern and mass resulted in an F-value of 2.93 with $p = 0.095$. Because this p-value exceeds 0.05, there is insufficient evidence to confirm a significant interactive effect at the 95% confidence level. This suggests that although each factor independently contributes to variations in voltage, their combination does not produce a meaningful synergistic effect.

Therefore, the observed significant effects are independent in nature, meaning that each main factor (pattern and mass) affects the voltage output separately. This conclusion is

consistent with the descriptive analysis presented earlier, which showed that jumping conditions produced higher voltages compared to walking, and heavier mass resulted in greater outputs than lighter mass.

In addition to presenting the two-way ANOVA results in tabular form, the analysis is further supported by graphical visualisation. The graphical representation offers a more intuitive perspective on the differences in mean voltage across various combinations of loading patterns and user masses. Through this visualisation, readers can more easily observe data tendencies, including group differences and potential interactions. The interaction plot of loading pattern and user mass is presented in Figure 9.

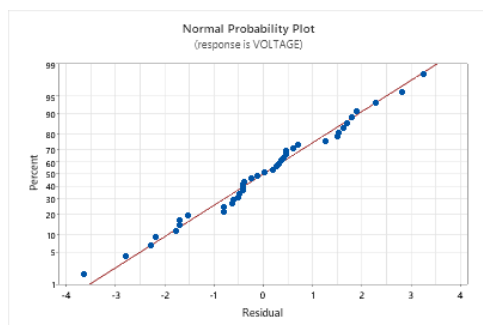


Figure 9. Interaction plot of the two-way ANOVA results for voltage using Minitab.

The figure presents the Normal Probability Plot of voltage residuals obtained from the two-way ANOVA test. In general, the residual data points closely follow the diagonal line, indicating that the residuals approximate a normal distribution. This condition fulfils one of the key assumptions of ANOVA, namely that residuals should be normally distributed.

A slight deviation is observed at the lower tail (extremely harmful residuals); however, this deviation remains within an acceptable range and does not compromise the overall validity of the model. Therefore, it can be concluded that the results of the two-way ANOVA for voltage are valid, as the assumption of residual normality is satisfied at the 95% confidence level. Meanwhile, the results of the two-way ANOVA for current, obtained using Minitab, are presented in Figure 10.

Analysis of Variance					
Source	DF	Adj SS	Adj MS	F-Value	P-Value
PATTERNS	1	442,89	442,890	192,95	0,000
MASS	1	173,47	173,472	75,57	0,000
PATTERNS*MASS	1	141,00	141,000	61,43	0,000
Error	36	82,63	2,295		
Total	39	840,00			

Figure 10. Results of a Two-Way ANOVA using Minitab for the current study.

The results of the two-way ANOVA indicate that both the loading pattern (patterns) and user mass (mass) significantly affect the output current of the piezoelectric floor prototype. The loading pattern factor produced an F-value of 192.95 with $p = 0.000$, while the mass factor yielded an F-value of 75.57 with $p = 0.000$. Both p-values are far below the significance threshold of $\alpha = 0.05$ (95% confidence level), confirming statistically significant differences between walking and jumping conditions, as well as between user masses of 69 kg and 98 kg.

Furthermore, the interaction between loading pattern and mass also produced a significant result, with an F-value of 61.43 and $p =$

0.000. Since the p-value is less than 0.05, it can be concluded that a meaningful interactive effect exists at the 95% confidence level. This implies that the combination of loading pattern and mass not only influences current output independently but also synergistically enhances it. In other words, the jumping condition at a higher mass (98 kg) generates substantially greater current output compared to other combinations.

Thus, the significant effects on current output are both independent and interactive. Each main factor (pattern and mass) contributes significantly, while their interaction amplifies the effect on the output current. This conclusion is consistent

with the earlier descriptive analysis, which showed that jumping produced a higher current than walking, and that higher mass resulted in greater current output, particularly when both conditions were combined.

To complement the two-way ANOVA results for the current output, a Normal Probability Plot of residuals is presented. This plot was selected because it directly demonstrates whether the residuals follow a normal distribution, which is a key assumption of ANOVA analysis. The visualisation of the two-way ANOVA results for current is shown in Figure 11.

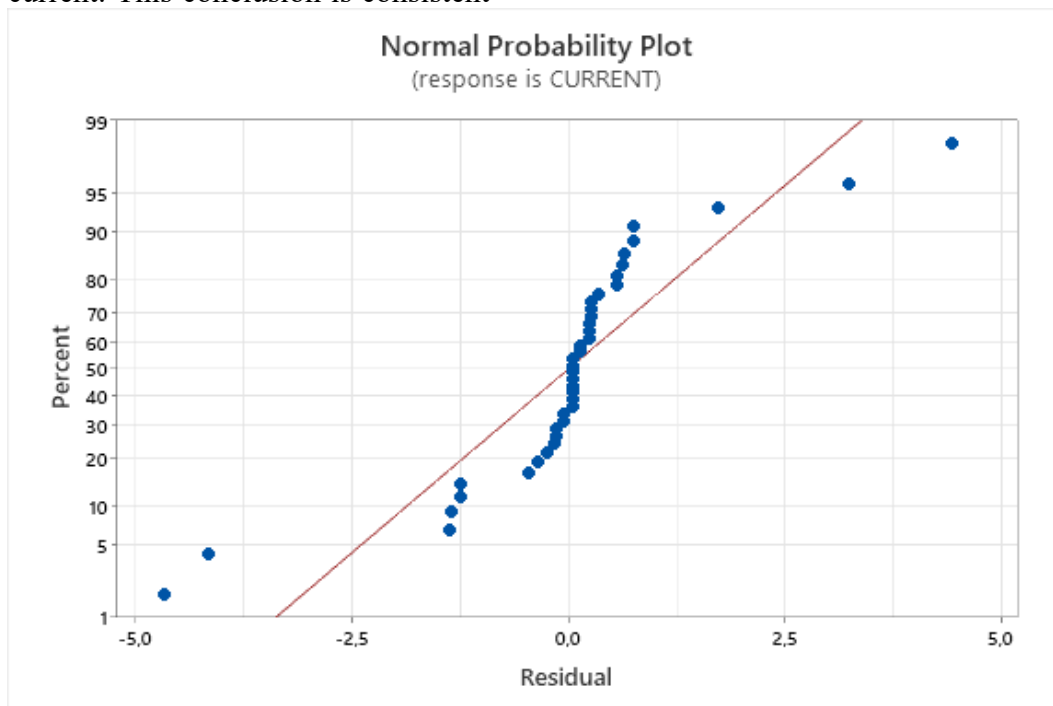


Figure 11. Interaction plot of the two-way ANOVA results for current using Minitab.

The figure presents the Normal Probability Plot of the residual current obtained from the two-way ANOVA. Overall, the residual points are closely aligned with the diagonal line,

indicating that the residuals approximately follow a normal distribution. This condition satisfies one of the key assumptions of ANOVA, namely residual normality. A minor deviation can be observed in

the lower tail (some extremely harmful residuals). However, such deviations remain within an acceptable range and do not compromise the model's validity. Therefore, it can be concluded that the two-way ANOVA on current is valid for interpretation, as the assumption of residual normality is fulfilled at the $\alpha = 0.05$ significance level (95% confidence level).

Taken together, the findings demonstrate that the performance of the piezoelectric floor prototype is significantly influenced by both the loading pattern and user mass. The descriptive analysis confirmed that the jumping pattern produces higher voltage and current compared to walking, while increased user mass further enhances the harvested energy output. The results of the two-way ANOVA support these observations, indicating that both loading pattern and mass have statistically significant effects on system output, with independent contributions to voltage and an interactive effect on current. These findings suggest that the piezoelectric floor design can achieve greater optimisation under dynamic loading conditions with heavier mass. Nevertheless, challenges remain regarding signal stability and energy conversion efficiency, underscoring the need for further improvements in mechanical design and power management systems to support the practical implementation of these systems in public spaces.

CONCLUSION

This study successfully designed and evaluated the performance of a PZT-based piezoelectric floor prototype configured in parallel, supported by a

spring-pillar mechanism as a force transmission medium. Experimental results indicate that loading patterns and user mass have a significant influence on the energy output characteristics. Walking patterns produced lower but more stable average voltage and current, whereas jumping patterns generated higher energy output accompanied by greater fluctuations. Moreover, an increase in mass was found to enhance system performance, with the optimal result observed under the jumping condition with a 98 kg load, yielding an average voltage of 8.9 V and a current of 11.67 mA.

Although the output current remains at a low milliamper scale, limiting its suitability for high-power applications, these findings demonstrate tangible potential for low-power applications. As suggested by Selim et al. (2024) Piezoelectric floor tiles are suitable for low-power applications, such as LED lighting or sensor systems. Our study further confirms that, despite limited current output, the system could drive IoT devices and LED lighting when integrated with appropriate energy storage and power management modules. For instance, harvested energy could be used to support Internet of Things (IoT) applications, such as energy-efficient LED lighting in public areas with high pedestrian traffic. To achieve practical implementation, the system must be coupled with suitable energy storage and power management units to stabilise the power supply and accommodate signal fluctuations.

Overall, these findings underscore the promising potential of piezoelectric flooring technology as

an environmentally friendly alternative energy source. Future research is recommended to focus on improving output stability, optimising piezoelectric configurations, and conducting field-scale testing to enable effective deployment in real-world contexts such as public spaces, smart buildings, and sustainable urban infrastructure.

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